Contents

Chapter 3

Detector Requirements

In this section, we present the main requirements on the design of the BTeV detector and provide an overview of the spectrometer design that we have developed to satisfy these requirements.

We begin with a discussion of the key "drivers" of the detector design:

- the physics of B production at $\sqrt{s}$ of 2 TeV;

- the final states we want to detect and study, based on the physics goals described above, and the associated backgrounds that must be suppressed;

- the characteristics of the Tevatron and the C0 collision region; and

- the required statistical precision.

After explaining the requirements of the design, we describe the baseline detector, which achieves BTeV's currently stated physics goals. A further requirement is that the detector be flexible – that it have the capability to study topics which may not be considered interesting today but which may be recognized to be important in the future.

In our original June 2000 proposal, the detector covered the angular region from 10 mr to 300 mr relative to the proton beam and from 10 mr to 300 mr relative to the anti-proton beam. We referred to each region of angular coverage as an "arm" of the spectrometer and described this as a "two arm" detector. Here we define a descoped version of the detector, which we call Phase 1, which covers only one of these two angular regions and is, therefore, a "single arm" detector. Figure 3.1 shows the full detector as originally proposed. A schematic of the Phase 1 detector is shown in Fig. 3.2. The new design is capable of carrying out the full program of measurements albeit on a longer time scale. The new design also permits the installation of components on the "uninstrumented side" later on.

The key design features of BTeV include:

- A dipole located on the IR, which permits BTeV to have an effective "two arm" acceptance. In Phase 1, only one arm is instrumented.
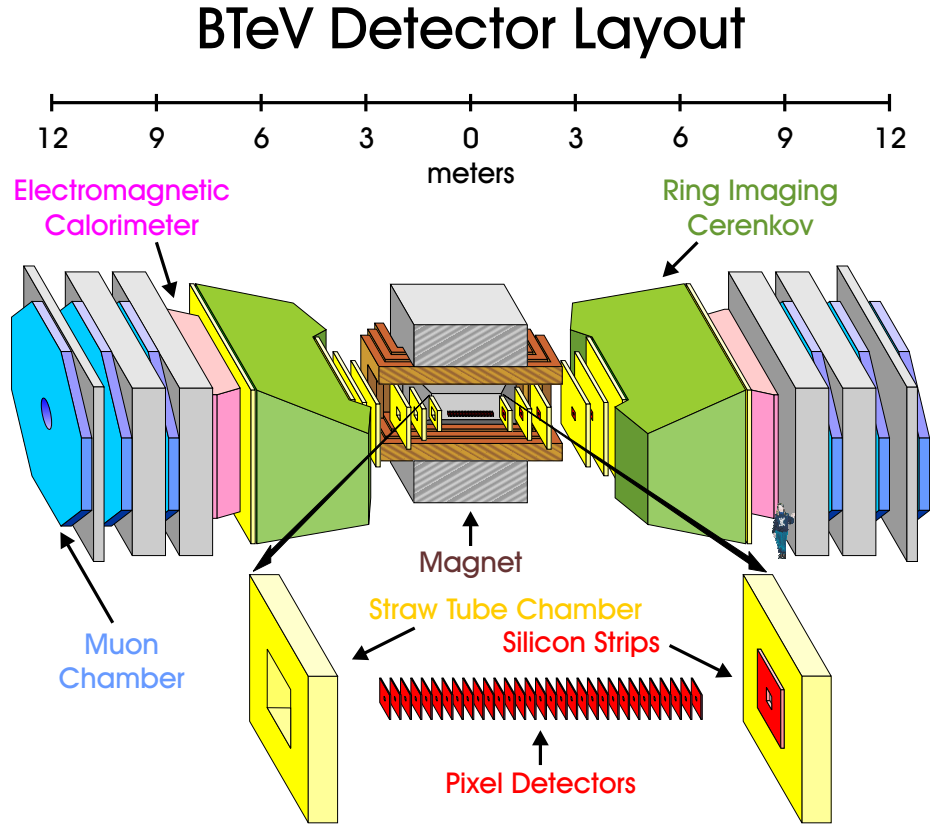
BTeV Detector Layout

Figure 3.1: Layout of original BTeV/C0 detector (both arms fully instrumented)

- A precision vertex detector based on planar pixel arrays;

- A detached vertex trigger at Level 1 which makes BTeV efficient for most final states, including purely hadronic modes;

- Precision tracking using straw tubes and silicon microstrip detectors, which provide excellent momentum and mass resolution out to 300 mr;

- Excellent particle identification using a Ring Imaging Cherenkov Detector (RICH). The RICH provides hadron identification from 3-70 GeV and lepton identification from 3-20 GeV, out to the full aperture of 300 mr, which is crucial since the muon detector and calorimeter do not cover the full solid angle.

- A high quality $PbWO_4$ electromagnetic calorimeter, covering 200 mr, capable of reconstructing final states with single photons, π^o's, η's or η''s, and identifying electrons;

- Excellent identification of muons out to 200 mr using a dedicated detector consisting
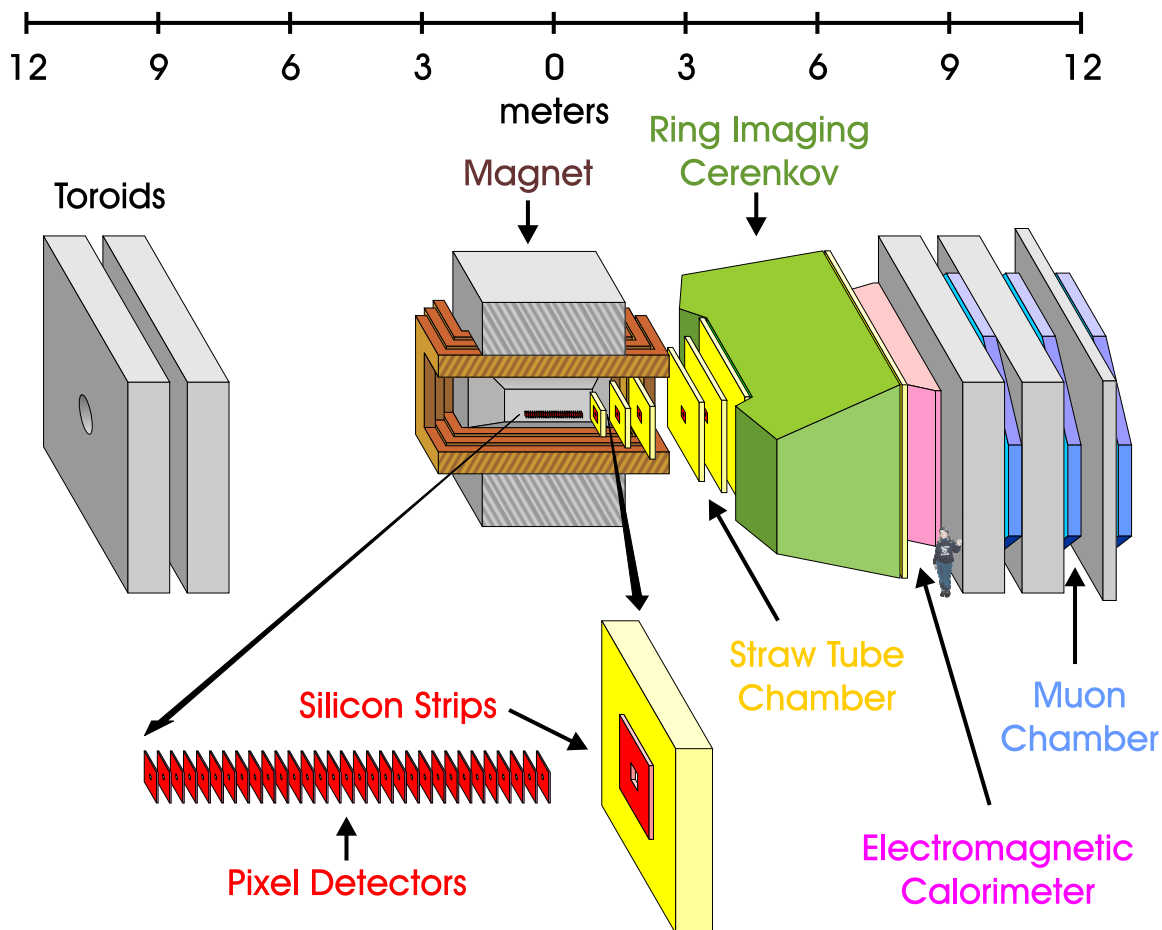
BTeV Detector Layout

Figure 3.2: Layout of BTeV Phase 1 Detector (only one arm instrumented)

of a steel toroid instrumented with proportional tubes. This system has the ability to supply a dimuon trigger; and

- A very high speed and high throughput data acquisition system which eliminates the need to tune the experiment to specific final states.

After reviewing the requirements that led us to these design principles, we provide, in the next chapter, a brief description of each major detector component. The level of detail is sufficient to provide the reader with a good overview of the experimental apparatus and a reasonable understanding of the solution to all the various problems associated with carrying out our ambitious program of studying B decays. However, we do not present every detail which an expert might need to understand the implementation and status of development of each detector technology, nor do we discuss the many calculations that went into the

optimization of the design. Additional information may be found in the proposal and in many writeups and reports, which are referenced in the text.

3.1 Requirements Based on the Physics of B Production at $\sqrt{s}$ of 2 TeV

The physics of hadronic beauty and charm production plays a major role in the design of BTeV. We review the most important features here. In hadron colliders all B species, B_d, B_u, B_s, b-baryons, and even B_c mesons, are produced at the same time. This allows one to carry out a very large number of interesting studies and to look for unexpected phenomena provided the detector is both powerful and flexible, especially in the area of triggering.

3.1.1 The $b\overline{b}$ Production Cross-Section

It is customary to characterize heavy quark production in hadron collisions with two variables, the momentum transverse to the beams, p_t, and the rapidity,

$$y = \frac{1}{2} \ln \left(\frac{E + p_\parallel}{E - p_\parallel} \right) , \tag{3.1}$$

where E is the particle's energy and $p_\parallel$ is its longitudinal momentum. Often, the pseudorapidity η

$$\eta = -ln \left(\tan \left(\theta/2 \right) \right) \quad , \tag{3.2}$$

where θ is the angle of the particle with respect to the beam direction, is used for the longitudinal variable since this variable is independent of the particle's mass.

The $p\overline{p}$ production of b quarks has been measured in the Tevatron at a center-of-mass energy of 1.8 TeV in the central rapidity region $|\eta| < 1$ by CDF [1] and D0 [2], and in the forward region $3.2 > y > 2.4$ by D0 [3]. Both CDF and D0 find that the $b\overline{b}$ production cross-section in the central region is underestimated by the Mangano, Nason and Ridolfi (MNR) next-to-leading order QCD calculation [7] by a factor of approximately two. Since the QCD calculation predicts a cross-section of 50 μb, when integrated over η and p_t, using the data in the central regions leads to a total $b\overline{b}$ production cross-section of 100 μb. The D0 central and forward data are shown in Fig. 3.3.

The measured cross-section in the higher y region is 3.6 ± 0.8 times higher than the QCD calculation, leading to a total estimated $b\overline{b}$ production cross-section of 180 μb. BTeV will operate in the range $1.9 > \eta > 4.5$. While we have no reason to dispute the D0 measurement, we will conservatively normalize our estimates to a $b\overline{b}$ production cross-section of 100 μb.

There is some evidence from HERA that the fragmentation of charmed particles is influenced by the leading quarks in the beam so that the fragmentation produces, in some cases, faster D's than the parent c-quarks [4]. This effect is expected to be smaller for b quarks at the center-of-mass Tevatron. If such an effect were present it would increase BTeV's acceptance in the forward direction.
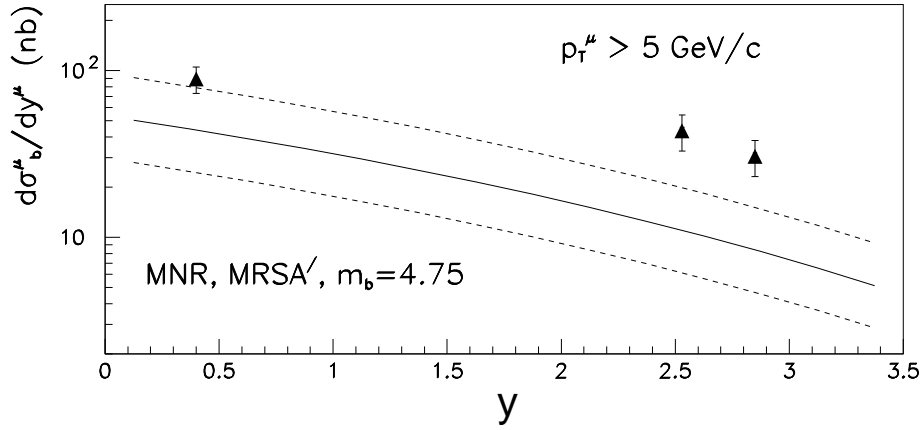
Figure 3.3: The $b\bar{b}$ cross-section as a function of the rapidity of muons from b decay, y^{μ}, measured by D0 for both the forward and central rapidity regions, using muons from b decays with $p_t > 5$ GeV/c. The solid curve is the prediction of the next-to-leading order QCD calculation for a b-quark mass of 4.75 GeV. The dashed curves represent the estimated theoretical 1σ error band.

The fact that the production cross section for states containing b-quarks is $\approx 1/500$ of the total cross section has strong implications for the design of the experiment. It means that the experiment must have a very good trigger to reject the very large number of typical interactions which involve only light quarks. It further means that the experiment will have to handle very high particle fluxes, and tolerate very high radiation doses, if it is going to get reasonable samples of the key decay modes it wants to study, especially given the well-known fact that the B decay modes most interesting for CP studies have rather small branching fractions.

3.1.2   Characteristics of Hadronic b Production

The dominant mechanism for b quark production at the Tevatron is believed to be gluon-gluon fusion. Whenever the two gluons have different Feynman-x, the center of mass of the produced $b - \bar{b}$ pair is boosted along the direction of the higher momentum gluon. Thus, we have an intrinsically asymmetric energy gluon-gluon collider. According to both simple arguments and detailed QCD calculations, the b's are produced approximately "uniformly" in η and have a truncated transverse momentum, p_t, spectrum, characterized by a mean value approximately equal to the B mass [5]. The distribution in η is shown in Fig. 3.4.

There is a strong correlation between the B momentum and η. Shown in Fig. 3.5 is the $\beta\gamma$ of the B hadron versus η from the Monte Carlo physics generator Pythia at $\sqrt{s} = 2$ TeV. It can clearly be seen that near η of zero, $\beta\gamma \approx 1$, while at larger values of $|\eta|$, $\beta\gamma$ can easily reach values of 6. This is important because the observed decay length varies with $\beta\gamma$ and, furthermore, the absolute momenta of the decay products are larger allowing for a suppression of the multiple scattering error.
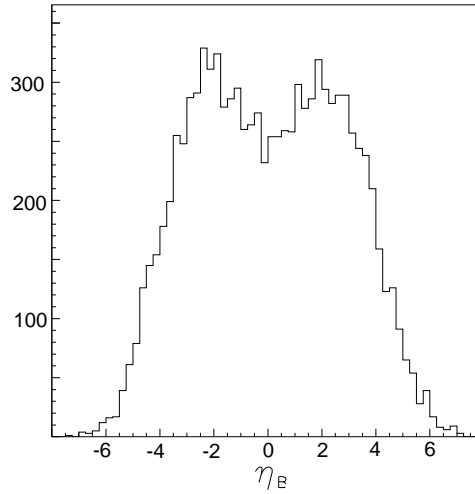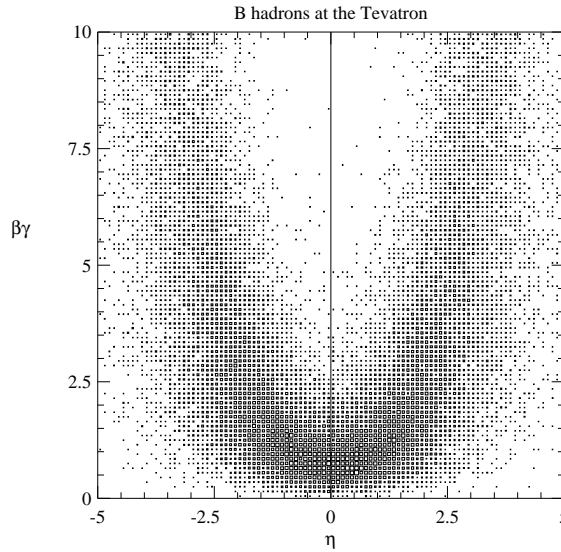
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Figure 3.4: The B yield versus η.

Figure 3.5: $\beta\gamma$ of the B versus η.

Since the detector design is somewhat dependent on the Monte Carlo generated b production distributions, it is important to check that the correlations between the b and the $\bar{b}$ are adequately reproduced. Fig. 3.6 shows the azimuthal opening angle distribution between a muon from a b quark decay and the $\bar{b}$ jet as measured by CDF [6] and compares it with the MNR next-to-leading order QCD predictions [7].

The MNR model does a good job representing the shape, which shows a strong back-to-back correlation. The normalization is about a factor of two higher in the data than the theory, which is generally true of CDF and D0 b cross-section measurements.

The "flat" η distribution hides an important correlation of $b\bar{b}$ production at hadronic colliders. In Fig. 3.7 the production angle of the hadron containing the b quark is plotted versus
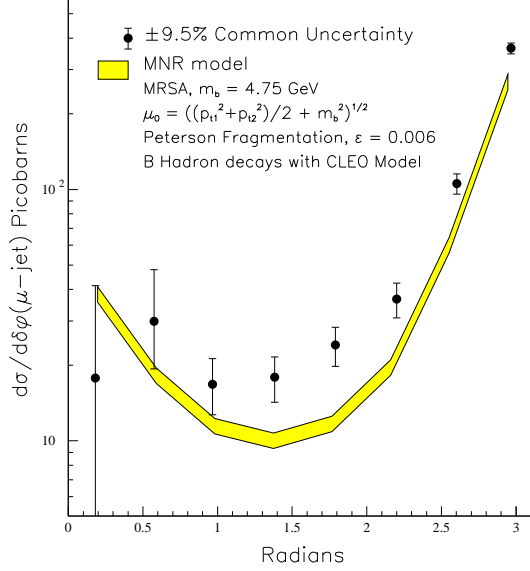
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Figure 3.6: The differential $\delta\phi$ cross-sections for $p_T^\mu > 9$ GeV/c, $|\eta^\mu| <$0.6, $E_T^{\bar{b}} >$10 GeV, $\left|\eta^{\bar{b}}\right| < 1.5$ compared with theoretical predictions. The data points have a common systematic uncertainty of $\pm9.5\%$. The uncertainty in the theory curve arises from the error on the muonic branching ratio and the uncertainty in the fragmentation model.

the production angle of the hadron containing the $\bar{b}$ quark. Here zero degrees represents the direction of the incident proton and 180 degrees, the incident anti-proton. There is a very strong correlation in the proton or the anti-proton directions: when the B is forward the $\overline{B}$ is also forward. (We call both the proton and anti-proton directions forward.) This correlation between B and $\overline{B}$ production is not present in the central region (near 90 degrees). This is a result of the underlying physics of gluon-gluon collisions described above.

In the forward direction, this correlation is crucial to carrying out studies that involve flavor tagging. For many B decay studies that involve mixing, it is necessary to determine the flavor of the signal B hadron at the moment of production. One way to do this is to determine the flavor of the "other" B hadron. Because of the correlated nature of the b-quark production, both B hadrons will be boosted in the same direction and therefore the signal and the tagging decay products will appear in the same "arm". Were this not true, it would be impossible to do these measurements with a single arm detector.

Thus, the forward direction at the Tevatron presents us with a number of striking advantages. First of all, there is a large cross-section for the production of correlated $b\bar{b}$ pairs. Secondly, the B hadrons that are formed have relatively large momenta, on average 30 GeV/c, and their decay products are not too badly affected by Multiple Coulomb Scattering. This allows us to make precision measurements of their spatial origins; so we can determine if they arise from B hadrons that traveled on the order of several mm prior to their decay. Furthermore the geometry is very natural for certain aspects of detector technology that significantly enhance the physics performance. For example, a Ring Imaging
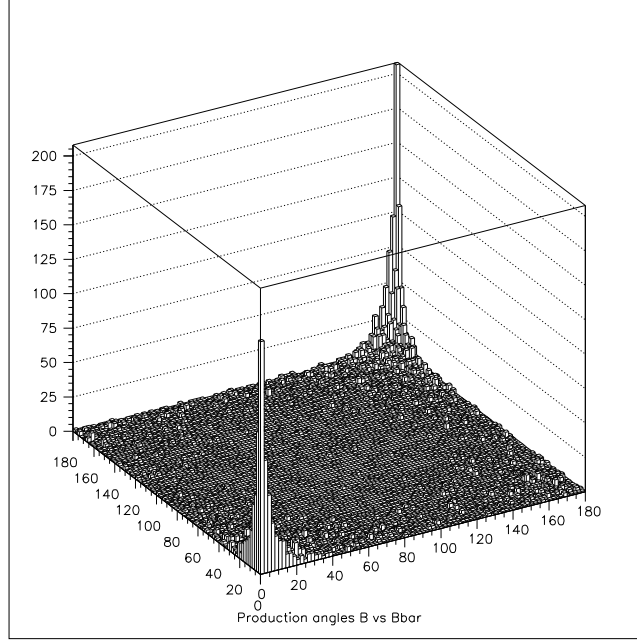
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Figure 3.7: The production angle (in degrees) for the hadron containing the b quark plotted versus the production angle for the hadron containing the $\bar{b}$ quark in the same event, from the Pythia Monte Carlo generator.

Cherenkov detector using a gas radiator matches the 3-70 GeV/c momentum range for B decay products. The Cherenkov photons can be detected using a relatively small area array of photomultiplier tubes or Hybrid PhotoDiodes(HPDs). Powerful particle identification is essential for high sensitivity b experiments. Another example is the ability to put the silicon pixel vertex detector inside the main beam vacuum. Precision detection of the B decay vertices is crucial for the trigger and in rejecting backgrounds. For these reasons, we have designed a detector with "forward coverage."

Charm production is similar to b production but has a much larger cross section. Current theoretical estimates are that charm is 1-2% of the total $p\bar{p}$ cross-section. The cross section is even more strongly peaked in the forward direction because the average transverse momentum is of the order of only 1.5 GeV/c. The charm cross section has never been measured because experiments with good acceptance in the central region have very low efficiency for triggering and reconstructing charm. The favorable kinematics in the forward direction gives BTeV a very high efficiency for reconstructing charm.

3.2 Requirements Based on the Characteristics of B Decay Modes

The physics case described above involves reconstructing a variety of different decay modes of the B, B_s, and other B hadrons and, in many cases, following their time evolution, and tagging the flavor of the parent B at production and at the moment of decay. These decay modes may involve charged hadrons, charged leptons, photons (prompt or from π^o's), and tertiary vertices from the $b \rightarrow c$ decay chain. In some cases, there are substantial backgrounds from minimum bias (typical hadronic) events, charm decays, or other B decays. In many cases, the branching fractions, including any tertiary decays, are quite small, typically 10^{-5} to 10^{-7}. This, together with the large background of minimum bias events, demands that BTeV be able to reconstruct multibody final states, with good resolution in invariant mass, and to handle very high rates. In order to carry out the physics program described above, the detector must have the ability to separate decay vertices from the primary interaction vertex and to reconstruct secondary B vertices and daughter charm vertices. This requires a precision vertex detector. It also must be able to measure the time evolution of decays for time-dependent asymmetry studies. The most demanding requirement is to be able to follow the very rapid oscillations of the B_s meson in order to study CP violation. It must have the ability to distinguish pions, kaons, and protons from each other to eliminate kinematic reflections that can contaminate signals and make them difficult to observe. Many key decay modes have π^o's, γ's, or particles that decay into them, such as ρ's or η's. Leptons, muons and electrons (positrons), appear in many key final states so good lepton identification is also required. Finally, many of the detector properties which are needed to isolate and reconstruct signals are also needed to perform "flavor tagging."

We illustrate the full range of capabilities required for BTeV by choosing a particular menu of physics measurements related to CP violation in B decays. These by no means constitute the full range of measurements that we plan to make but comprise a basic set of very crucial measurements which do constrain the CKM triangle. These translate into a basic set of requirements for the detector, shown in Table 3.1. In the table, we list physics topics, a particular decay mode that can be used to study it, and then tabulate the key features necessary to reconstruct the signal and perform flavor tagging where required. It can be seen that in order to carry out this program, the detector must make a complete characterization of the final state particles. A table prepared to address the topic of rare decays would have similar characteristics. It should be clear that a device with these properties, combined with a very powerful and inclusive trigger system for B decays and a high speed data analysis system, can address a very large range of topics.

Table 3.1: Some crucial measurements and corresponding detector requirements. In order to separate signals and background, all studies in BTeV need good primary and secondary vertex resolution, which is equivalent to a requirement on the resolution in proper time, τ, of a small fraction of the B lifetime. The requirement of "superb τ resolution", referred to in this table, means resolution which is a small fraction of the expected period for B_s mixing and is a much more stringent requirement. The "lepton id" is checked where it is used to extract the signal decay, although it participates in most of the other studies via lepton flavor tagging.

Physics Quantity	Decay Mode	Detector Property				
		Vertex trigger	K/π separation	γ detection	superb τ resolution	lepton id
$\sin(2\alpha)$	$B^o \to \rho\pi \to \pi^+\pi^-\pi^o$	$\surd$	$\surd$	$\surd$		
$\cos(2\alpha)$	$B^o \to \rho\pi \to \pi^+\pi^-\pi^o$	$\surd$	$\surd$	$\surd$		
$\mathrm{sign}(\sin(2\alpha))$	$B^o \to \rho\pi, B^o \to \pi^+\pi^-$	$\surd$	$\surd$	$\surd$		
$\sin(\gamma)$	$B_s \to D_s K^-$	$\surd$	$\surd$		$\surd$	
$\sin(\gamma)$	$B^+ \to D^o K^+$	$\surd$	$\surd$			
$\sin(\gamma)$	$B \to K\pi$	$\surd$	$\surd$	$\surd$		
$\sin(\gamma)$	$B \to \pi^+\pi^-, B_s \to K^+K^-$	$\surd$	$\surd$		$\surd$	
$\sin(2\chi)$	$B_s \to J/\psi\eta', J/\psi\eta$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
$\sin(2\beta)$	$B^o \to J/\psi K_s$					$\surd$
$\sin(2\beta)$	$B^o \to \phi K_s, \eta' K_s, J/\psi\phi$	$\surd$	$\surd$	$\surd$		$\surd$
$\cos(2\beta)$	$B^o \to J/\psi K^*, B_s \to J/\psi\phi$					$\surd$
x_s	$B_s \to D_s\pi^-$	$\surd$	$\surd$		$\surd$	
$\Delta\Gamma$ for B_s	$B_s \to J/\psi\eta', K^+K^-, D_s\pi^-$	$\surd$	$\surd$	$\surd$		$\surd$

3.3 Requirements Due to Characteristics of the Tevatron and the C0 Interaction Region

For reasons related to radiation damage and triggering, among others, we have concluded that BTeV will become rate limited somewhere between 2 and $5\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. (This depends on many technology and budget issues). Since BTeV would begin after many years of Tevatron operation for Run 2, we assume that a luminosity of 2×10^{32} will be available to us. We have designed BTeV to run at that luminosity (with the ability to handle at least another factor of two with increased triggering hardware and possible limited detector upgrades). We also have made sure that the design permits the full instrumentation of the second arm.

Table 3.2 gives the Tevatron parameters which are especially relevant to BTeV design and physics reach. We expect to start serious data taking with a luminosity of about $5 \times$

10^{31} cm^{-2}s^{-1}; our design luminosity goal is 2×10^{32} cm^{-2}s^{-1}. At the higher luminosity we expect an average of 2 total interactions per crossing, 1.3 of which are not elastic or quasi-elastic.

Table 3.2: The Tevatron as a b and c source for BTeV

Luminosity (BTeV design)	2×10^{32} cm^{-2}s^{-1}
$b\bar{b}$ cross-section	100 μb
# of b's per 10^7 sec	4×10^{11}
$\frac{\sigma(b\bar{b})}{\sigma(total)}$	$\sim 0.15\%$
$c\bar{c}$ cross-section	> 500 μb
Bunch spacing	132 ns
Luminous region length	$\sigma_z = 10\text{-}20$ cm (crossing angle dependent)
Luminous region width	$\sigma_x, \sigma_y \approx 50$ μm
Interactions/crossing	$< 2.0 >$

3.4   Summary

BTeV will be a second generation study of CP violation in B decays. The experiments at the asymmetric B-factories, BABAR at PEPII and BELLE at KEKB, will have made many measurements of CP violation and rare decays of the B_d and B_u hadrons. CDF and D0, running at the Tevatron, will also carry out some of these measurements and will begin to study the decays of the B_s and other B hadrons. BTeV will do these studies at much higher precision and will augment them with crucial high-precision studies of B_s decays along with a program of studies of B_c and b-baryon decays. On about the same time scale as BTeV, LHCb will go into operation with similar capabilities for all-charged states, although without a high quality calorimeter or as inclusive a trigger. ATLAS and CMS will also be capable of doing some B-physics, especially for states containing leptons which are easy for them to trigger on.

In order make the best measurements on a wide range of B decays, we must accumulate large samples of reconstructed B decays. The Tevatron operating as described above produces enough B-hadrons for us to achieve our physics goals. The detecter must be able to operate at the high radiation levels implied by the high luminosity, must have excellent triggering capability, and be able to reconstruct B hadrons and tag their flavor with very high efficiency. The detector we describe in detail in the next chapter, whose design was driven by all the requirements and considerations we have discussed, achieves this goal.

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